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0 810 6684001 Patents ADP number *(if you know it)*		
If the applicant is a corporate body, give the country/state of its incorporation	United Kingdom	
4. Title of the invention	Superconducting Magnet Systems	
5. Name of your agent *(if you have one)*	Marks & Clerk	
"Address for service" in the United Kingdom to which all correspondence should be sent *(including the postcode)*	4220 Nash Court Oxford Business Park South Oxford OX4 2RU United Kingdom	
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Richard Harding
01865-397900

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"Superconducting Magnet Systems"

This invention relates to superconducting magnet systems.

Superconducting magnet systems, such as are used in nuclear magnetic resonance (NMR) spectroscopy and magnetic resonance imaging (MRI) and Fourier-transform mass spectroscopy (FTMS), incorporate a cryogenic vessel for containing the cryogenic fluid (normally liquid helium) to maintain the superconducting magnet at the required very low temperature of less than 4.2 K.

NMR spectroscopy requires not only high magnetic field strengths but also extremely high spatial homogeneity of the magnetic field that is generated, since resolution is limited by the absolute homogeneity of the magnetic field. The attainment of higher magnetic field strengths requires compromises in terms of field homogeneity and field stability, meaning that higher magnetic field strengths tend to improve resolution.

GB 2254409A discloses a NMR magnet system capable of generating very high magnetic field strengths by utilising a superconducting magnet operated at a lower operating temperature than the normal temperature of liquid helium (4.2 K). To this end the NMR magnet system has a cryogenic vessel incorporating a first chamber containing liquid helium at a temperature of less than 4.2 K, and a second chamber containing liquid helium at atmospheric pressure at a temperature of about 4.2 K. The second chamber is located below the first chamber within the vessel, and the first and second chambers are interconnected by a feed tube so that liquid helium from the second chamber may be supplied to the first chamber at standard pressure and temperature and may then be cooled by pumping down through a choke to a non-equilibrium state. In this arrangement replenishment of liquid helium utilises gravitational feed which can increase the overall height of the system and add a degree of complexity that can cause blockages and also an increase in helium consumption. Furthermore such an arrangement limits the extent to which the temperature of the

liquid helium cooling the magnet can be dropped, due to cooling losses within the system.

It is an object of the invention to provide a superconducting magnet system that can be operated at temperatures down to below the lambda point (2.17 K), and are therefore capable of producing magnetic fields of high strengths and homogeneity.

According to the present invention there is provided a superconducting magnet system comprising a cryogenic vessel, a superconducting magnet contained in an inner chamber within the vessel to be cooled by liquid helium within the inner chamber, and supply means for supplying current to the magnet by way of a supply passage extending through the wall of the vessel in order to initiate superconducting current flow in the magnet, wherein the supply means is in the form of a lead having a connector part at one end that is adapted (i) to be connected to a connector part provided on the magnet internally of the chamber in order to supply current from an external current source to the magnet by way of the lead extending through the supply passage to initiate superconducting current flow in the magnet, and (ii) to be subsequently detachable from the connector part, with the superconducting current flow persisting in the magnet, to permit withdrawal of the lead from the supply passage so as to limit heat conduction along the supply passage during further operation of the system

Such a superconducting magnet system is capable of being operated at very low temperatures down to below the lambda point, and of producing magnetic fields of high strengths and homogeneity suitable for NMR spectroscopy. In preferred embodiments of the invention the overall height of the system is decreased and the complexity of the system is simplified as compared with known systems, with consequent decreases in blockages and in helium consumption.

In a preferred system in accordance with the invention, the inner chamber is contained within an outer chamber to be cooled by liquid helium within the outer chamber, and the inner chamber is connected to the outer chamber by an

interconnecting feed tube for the purpose of occasionally replenishing the inner chamber with liquid helium from the outer chamber. The feed tube conveniently incorporates a needle valve for controlling the flow of liquid helium to the inner chamber.

In a preferred embodiment the inner chamber is arranged to contain liquid helium at reduced pressure boiling at a temperature of below 4.2 K, down to sub-lambda temperatures, and the outer chamber is arranged to contain liquid helium at normal atmospheric pressure boiling at a temperature of about 4.2 K.

In addition venting means may be provided for venting the inner chamber with helium gas without warming the liquid helium within the inner chamber to any substantial extent to permit the lead to be withdrawn from the supply passage.

Furthermore the arrangement is preferably such that, after withdrawal of the lead from the supply passage, the magnet is capable of being cooled by the liquid helium within the inner chamber down to temperatures below the lambda point.

In order that the invention may be more fully understood, a preferred embodiment of superconducting magnet system in accordance with the invention will now be described, by way of example, with reference to the accompanying drawings, in which:

Figure 1 is an axial section through the embodiment;

Figure 2 is an axial section through a known lambda point refrigeration system; and

Figure 3 is an axial section through a removable current lead of the embodiment of Figure 1.

The superconducting magnet system of Figure 1 of the drawings is intended for high field NMR spectroscopy. However it will be well understood that similar systems may be used in other applications.

Referring to Figure 1 the superconducting magnet system comprises an annular cryogenic vessel 1 (shown in axial section so that only two opposite parts angularly offset by 120 degrees relative to one another can be seen in the figure) having an outer vacuum container 4 and containing a superconducting magnet 11 comprising magnet coils (not shown in detail). The magnet 11 is housed within an inner chamber inside a stainless steel annular reservoir 16 containing liquid helium, the magnet 11 and the reservoir 16 being suspended from the top wall of an outer vacuum container 4 by means of high tensile GRP rods (not shown). An outer chamber containing liquid helium is defined within a secondary stainless steel annular reservoir 7 surrounding the reservoir 16. Furthermore a gas-cooled solid shield 6 made of high conductivity aluminium surrounds the secondary reservoir 7 and is cooled mainly by cold evaporating helium gas from the reservoirs 16 and 7. Finally the gas-cooled shield 6 is surrounded by a liquid nitrogen reservoir 5 containing liquid nitrogen (LN2) that boils at 77 K.

The rods supporting the magnet 11 and the reservoir 16 are thermally linked to the various cold radiation shields (that is the gas-cooled shield 6 and the other shields forming the reservoir walls etc) in order to reduce conducted heat input. Furthermore the reservoir 16 is provided with a single neck 17 extending through the top wall of the outer vacuum container 4 and defining a supply passage containing the current lead 19 to the magnet 11 as well as other electrical connecting leads, including the lead to a liquid helium level monitor 15 within the inner chamber. The neck 17 also provides a passage for evaporating gas streams providing thermal links to the radiation shields. In the case of the gas-cooled shield 6 the cold gas reduces the temperature of the shield and thereby improves its efficiency.

The secondary reservoir 7 is suspended from the top wall of the outer vacuum container 4 by means of three necks 18 extending through the top wall (two of these

necks being visible in the figure). The secondary reservoir 7 can easily be filled with liquid helium by way of a fill port (not shown) in one of the necks 18. The necks 18 are also thermally linked to the radiation shields providing further cooling by means of the evaporating gas streams within the necks 18. The gas-cooled shield 6 is not as heavy as the reservoirs 16 and 7 and is easily supported from the necks 17 and 18. The liquid nitrogen reservoir 5 is provided with three necks 13 by means of which it is suspended from the top wall of the outer vacuum container 4, the necks 13 providing exhausts for the cold LN2 gas.

The reservoirs 16 and 7 contain liquid helium that normally boils at 4.2 K at atmospheric pressure. However, in order to enhance the properties of the superconducting wire from which the magnet coils are wound, the temperature of the liquid helium in the inner chamber within the reservoir 16 is reduced to below the lambda point (2.17 K) by reducing the pressure above it by means of a rotary pump (not shown) connected to an exhaust outlet 2 connected to the neck 17. As well as acting as a cold radiation shield, the secondary reservoir 7 is used to replenish the reservoir 16 with liquid helium. At a predetermined low level of the helium within the reservoir 16 as indicated by the level monitor 15, a needle valve 9 within a feed tube 10 interconnecting the reservoirs 16 and 7 is opened so as to permit helium to flow from the secondary reservoir 7 to the reservoir 16 by virtue of the higher pressure in the reservoir 7.

When the liquid helium in the reservoir 16 has reached a predetermined high level in the reservoir 16 as determined by the level monitor 15, the needle valve 9 is closed so as to prevent any further liquid flow along the feed tube 10 from the reservoir 7 to the reservoir 16. The needle valve 9 may be operated manually or under the control of an automatic control circuit receiving inputs from the level detector etc, and may be operated so as to place the valve in an open, closed or partially closed condition. When the valve is opened helium flow takes place from the reservoir 7 to the reservoir 16 due to the pressure difference between the two reservoirs.

In addition to supplying liquid helium to replenish the reservoir 16, the secondary reservoir 7 acts as a thermal shield to the reservoir 16 so as to reduce the evaporation of helium from the reservoir 16 and facilitate the attainment of sub-lambda temperatures. The large amount of cold or superfluid helium present ensures that, in the event of a failure of the pumping system, the temperature of the magnet will not rise to a critical level for a very long time. Also the secondary reservoir 7 increases the time between liquid refills under normal operation which, in turn, minimises disruption to the NMR experiment.

The simplicity of construction ensures flexibility of attainable temperatures all the way down to 1.8 K and even lower, as well as allowing the outgoing cold helium gas to cool the thermal radiation shields in the most natural way, thus reducing heat input to the reservoirs 7 and 16. Since the secondary reservoir 7 contains liquid at normal atmospheric pressure, it is easily refilled with liquid helium from an external source in conventional manner.

By contrast, Figure 2 is an axial section through a known lambda-point refrigerator. In this case the magnet 20 is accommodated within a helium reservoir 21 which is itself surrounded by a LN2 shield 25 and gas-cooled radiation shields 24. The liquid helium is drawn into a refrigerating element 21 by a rotary pump connected to the exhaust outlet 26, a needle valve 22 being provided to throttle the liquid flow to allow low pressure in the refrigerating element 21 and hence a lower temperature for the boiling helium. The surrounding liquid in the reservoir 20 is cooled by conduction and falls to the bottom of the reservoir 20 due to its higher density. A thermal barrier 29 is provided to help prevent conduction of helium in the upper part of the reservoir 20 at 4.2 K to the lower part of the reservoir 20 at lower temperature.

Such a known lambda-point refrigerator suffers from a number of disadvantages in that devices are necessary to prevent a dangerous build up of pressure should the magnet quench, and it is difficult to attain a temperature below 2 K using such an arrangement. Furthermore special means are required to ensure correct setting of the

needle valve, and moreover the needle valve is prone to blocking, especially if the refrigerator runs out of liquid.

Both such a lambda-point refrigerator and the prior arrangement of GB 2254409A rely on replenishment of liquid helium by gravitational feed from an upper chamber, and these approaches increase the overall height of the system and add a degree of complexity which can cause blockages and also an increase in helium consumption.

Reverting to the embodiment of the invention shown in Figure 1, the magnet 11 is initially energised with current by way of a removable current lead 19 extending along the passage within the neck 17, the current lead 19 being removed completely from the neck 17 once the magnet 11 has been fully energised such that superconducting current flow persists in the magnet coils in spite of the disconnection of the lead 19. The consequential fall in temperature stabilises the magnetic field resulting in very low field decay, as is essential for NMR experiments.

Figure 3 diagrammatically shows the removable current lead 19 that comprises a shaft 30 extending through the neck 17 and connected to the top of the neck 17 by a leak-tight sealing flange 32 and flexible bellows 31. In additional the shaft 30 is provided with an exhaust outlet 33 for the exhaust of cold helium gas which enters at the bottom of the shaft 30 through vent holes (not shown). At the top of the lead 19 are positive and negative current terminals 41 and 42 surrounded by insulating bushes 47 and 48, a connecting cable (not shown) being provided for fitting to the top of the lead 19 to establish a connection to an external power supply for energising the magnet. The connections from the top of the lead 19 to the external power supply are made by way of two bolted on solid copper clamps fixed to the terminals 41 and 42. The power supply is located on a bench approximately 12 metres away from the magnet and outside the dangerously high stray field from the magnet. Substantial copper cables carry the current from the power supply to the magnet.

The bottom of the lead 19 is provided internally with positive and negative current connections 43 and 44 surrounded by an insulating bush 49 for the purpose of contacting positive and negative current connections 45 and 46 separated by an insulating bush 40 on a contact part of the magnet when the current lead 19, with the power supply connecting cable attached, is pushed downwardly within the neck 17 (possibly with a slight twisting motion) so that the lower part of the shaft 30 engages over the connector part of the magnet and establishes an electrical connection therewith. The connections 43 and 44 may be of a known type and incorporate a series of circumferentially spaced springs for biasing the connections into electrical contact with the connections 45 and 46 on the magnet when the lower part of the shaft 30 engages over the contact part. The positive and negative current connections 43 and 44 at the bottom of the lead 19 are connected to the positive and negative current terminals 41 and 42 at the top of the lead 19 by way of coaxial brass conductors (not specifically shown in the figure). At various stages of magnet operation the temperature of the lead 19 can change, causing thermal expansion and contraction and these can be accommodated by the flexible bellows 11.

During energisation of the magnet with current supplied along the lead 19, the reservoir 16 within which the magnet is accommodated is full of super-cooled liquid helium at low pressure. However, when the magnet has been suitably energised, it is essential that the lead 19 is removed from the neck 17 so as to allow sub-lambda temperatures to be achieved and hence a stable magnetic field. In order to permit the lead 19 to be removed, and also to enable the lead 19 to be connected to the magnet, the reservoir 16 must first be vented with helium gas and brought up to atmospheric pressure. To this end a gas bottle containing helium gas is connected by means of a "T" fitting and a one-way valve to the pumping line linking the pump to the exhaust outlet 2. The pump is then switched off and the valve opened so that helium gas flows from the gas bottle into the space above the magnet, until atmospheric pressure is achieved. The gas is allowed to flow for a few more minutes through the valve in the pumping line before the lead 19 is inserted or removed.

It has been determined empirically that this can be done without any significant warming of the supercold liquid helium in the reservoir 16 occurring over a period of several hours. This therefore provides sufficient time for detachment of the lead 19, with the power supply connecting cable attached, from the magnet by pulling hard on the lead 19 (possibly accompanied by a twisting motion) so that the lower part of the shaft 30 becomes detached from the connector part. The lead 19 can then be completely withdrawn from the neck 17, with the top of the neck 17 being subsequently capped to limit heat conduction along the neck 17. The cap used for this purpose is simply a blank flange with an outer edge having a similar profile to the flange 32 that it replaces.

CLAIMS:

1. A superconducting magnet system comprising a cryogenic vessel, a superconducting magnet contained in an inner chamber within the vessel to be cooled by liquid helium within the inner chamber, and supply means for supplying current to the magnet by way of a supply passage extending through the wall of the vessel in order to initiate superconducting current flow in the magnet, wherein the supply means is in the form of a lead having a connector part at one end that is adapted (i) to be connected to a connector part provided on the magnet internally of the chamber in order to supply current from an external current source to the magnet by way of the lead extending through the supply passage to initiate superconducting current flow in the magnet, and (ii) to be subsequently detachable from the connector part, with the superconducting current flow persisting in the magnet, to permit withdrawal of the lead from the supply passage so as to limit heat conduction along the supply passage during further operation of the system.

2. A system according to claim 1, wherein the inner chamber is contained within an outer chamber to be cooled by liquid helium within the outer chamber.

3. A system according to claim 2, wherein the inner chamber is connected to the outer chamber by an interconnecting feed tube for the purpose of occasionally replenishing the inner chamber with liquid helium from the outer chamber.

4. A system according to claim 3, wherein the feed tube incorporates a needle valve for controlling the flow of liquid helium to the inner chamber.

5. A system according to claim 2, 3 or 4, wherein the inner chamber is arranged to contain liquid helium at reduced pressure boiling at a temperature of below 4.2 K, down to sub-lambda temperatures, and the outer chamber is arranged to contain liquid helium at normal atmospheric pressure boiling at a temperature of about 4.2 K.

6. A system according to any preceding claim, wherein venting means is provided for venting the inner chamber with helium gas without warming the liquid helium within the inner chamber to any substantial extent to permit the lead to be withdrawn from the supply passage.

7. A system according to any preceding claim, wherein the arrangement is such that, after withdrawal of the lead from the supply passage, the magnet is capable of being cooled by the liquid helium within the inner chamber down to temperatures below the lambda point (2.17 K)

8. A system according to any preceding claim, wherein monitoring means is provided for monitoring the level of the liquid helium in the inner chamber.

9. A system according to any preceding claim, wherein a gas-cooled shield is provided within the vessel so as to surround the inner chamber.

10. A system according to any preceding claim, wherein an annular liquid nitrogen reservoir is provided within the vessel so as to surround the inner chamber.

11. A superconducting magnet system substantially as hereinbefore described with reference to Figures 1 and 3 of the accompanying drawings.

ABSTRACT

" Superconducting Magnet Systems"

A superconducting magnet system comprises a cryogenic vessel 1, a superconducting magnet 11 contained in an inner chamber 16 within the vessel 1 to be cooled by liquid helium within the inner chamber 16, and an outer chamber 7 containing liquid helium and linked to the inner chamber 16 by a feed tube 10 and a needle valve 9. A removable current lead 19 is provided for supplying current to the magnet 11 by way of a supply passage 17 extending through the wall of the vessel 1. The lead 19 has a connector part at one end that is adapted (i) to be connected to a connector part provided on the magnet 11 internally of the chamber 16 in order to supply current from an external current source to the magnet 11 by way of the lead 19 extending through the supply passage 17 to initiate superconducting current flow in the magnet 11, and (ii) to be subsequently detachable from the connector part, with the superconducting current flow persisting in the magnet 11, to permit withdrawal of the lead 19 from the supply passage 17 so as to limit heat conduction along the supply passage 17 during further operation of the system. Such a system is capable of being operated at very low temperatures down to below the lambda point, and of producing magnetic fields of high strengths and homogeneity suitable for NMR spectroscopy.

(Figure 1)

1/3

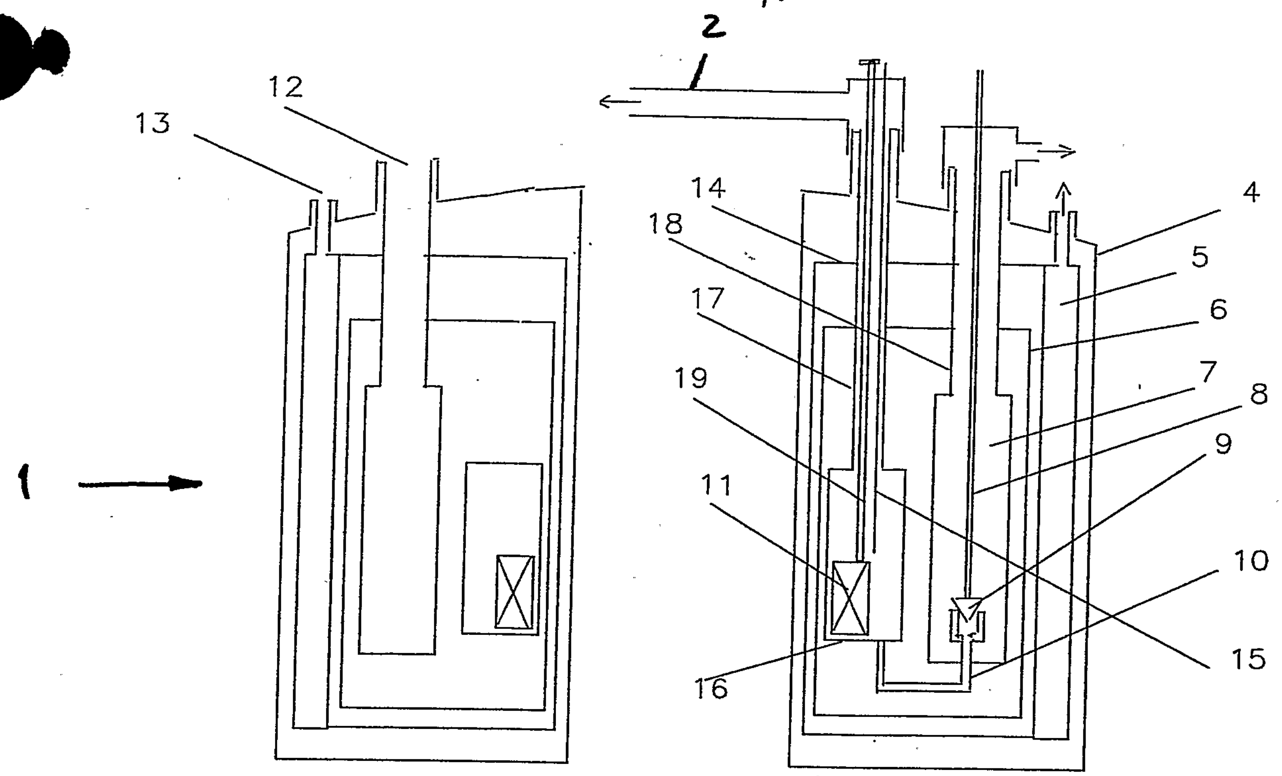

Fig 1 Dual helium can layout

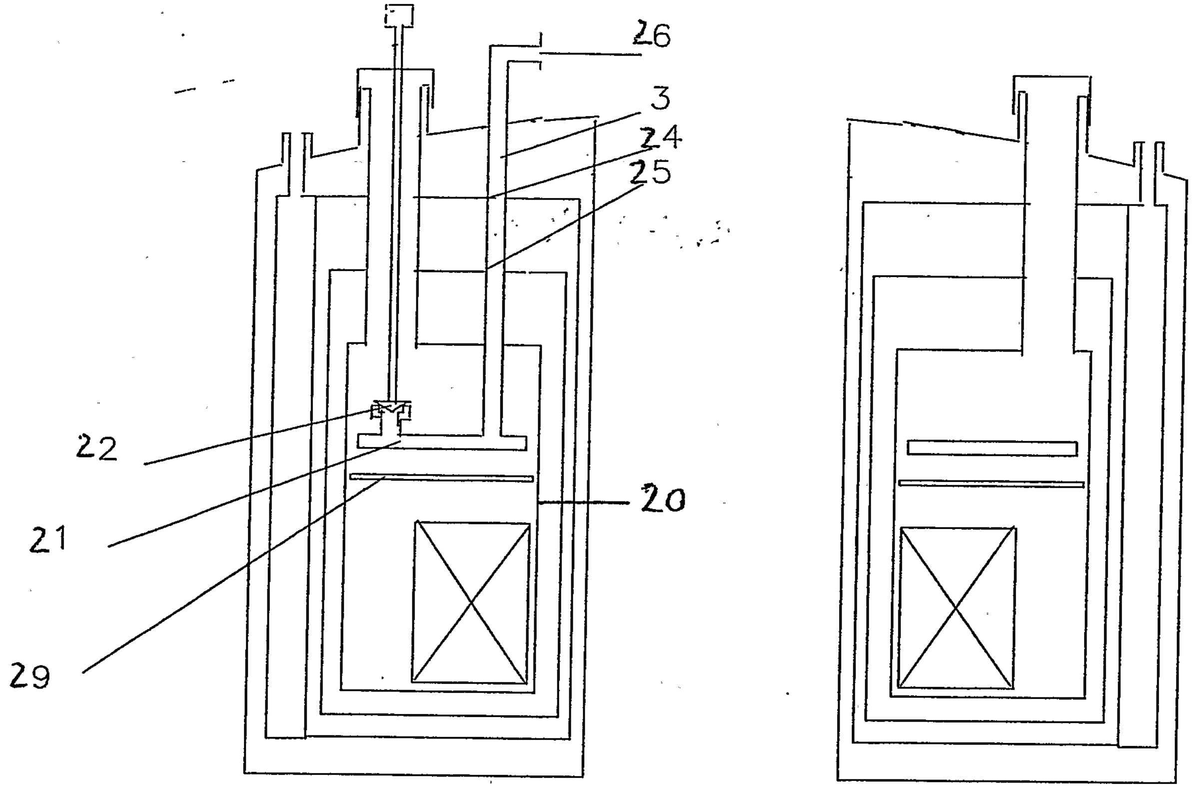

Fig 2. Essential elements of a traditional Lambda point refrigerator method

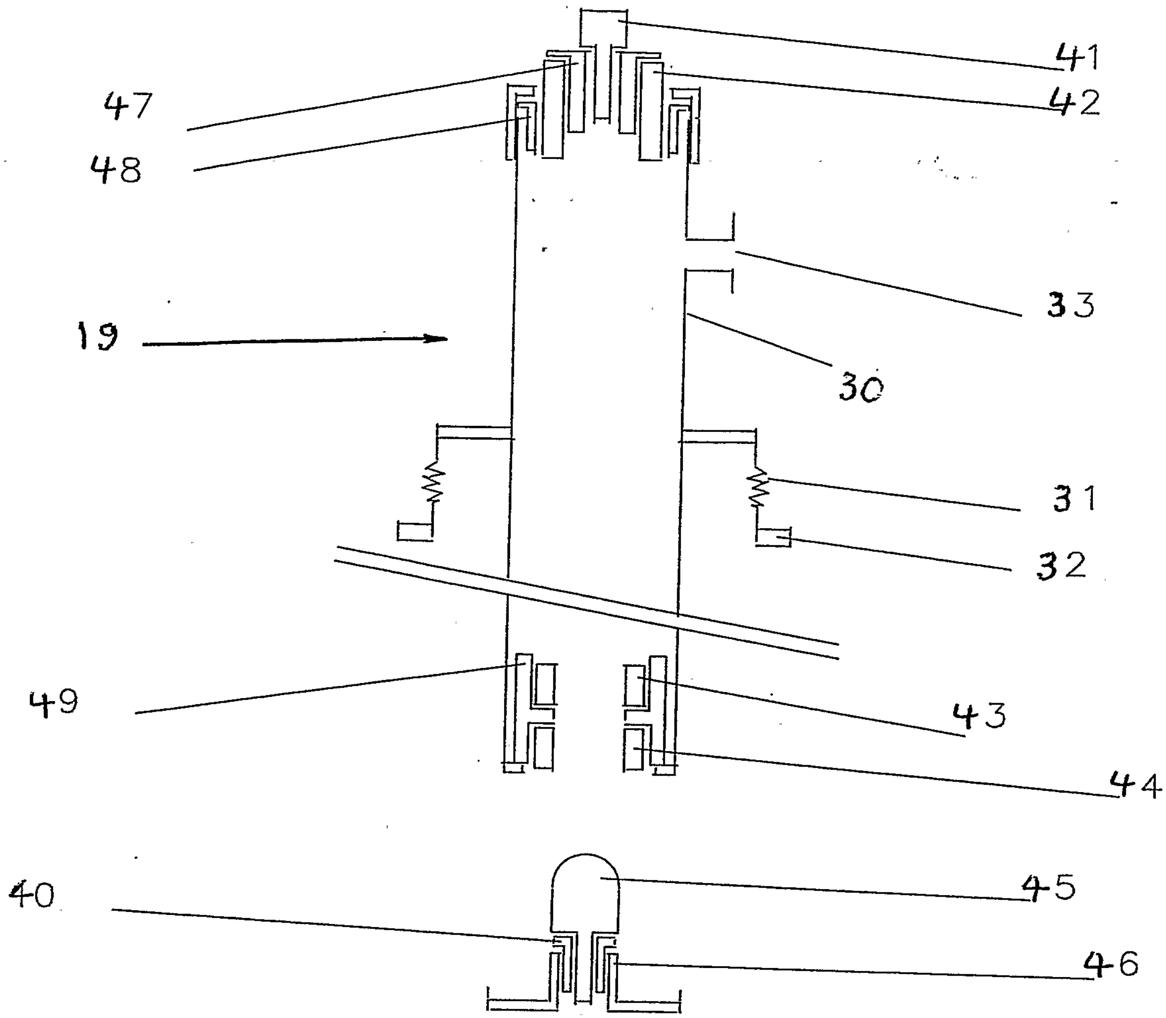

Fig. 3. Removable current lead